TITLE OF THE INVENTION

MAGNETORESISTIVE ELEMENT, MAGNETORESISTIVE HEAD AND
MAGNETIC REPRODUCING APPARATUS

CROSS-REFERENCE TO RELATED APPLICATIONS

5   This application is based upon and claims the
benefit of priority from the prior Japanese Patent
Application No. 2002-378648, filed December 26, 2002,
the entire contents of which are incorporated herein by
reference.

10   BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates to a
magnetoresistive element using a magnetoresistive film
in which a sense current is flowed in a direction

15   substantially perpendicular to the film surface,
a magnetoresistive head using the particular
magnetoresistive element, and a magnetic reproducing
apparatus having the magnetoresistive head installed
therein.

20   2. Description of the Related Art

In a certain type of a ferromagnetic material, it
is known that the electrical resistance is changed in
accordance with the intensity of an external magnetic
field. This particular phenomenon is called the

25   magnetoresistive effect and can be used for detecting
an external magnetic field. A field-sensing element
utilizing the magnetoresistive effect is called

a magnetoresistive element, hereinafter referred to as an "MR element" in some cases.

The MR element is utilized in a magnetic head for reading information stored on a magnetic recording medium in a magnetic reproducing apparatus utilizing a magnetic recording medium such as a hard disk or a magnetic tape, and the particular magnetic head is called an MR head.

In recent years, magnetic recording density is being made higher in the magnetic recording-reproducing apparatus utilizing the MR head, particularly, in a hard disk apparatus, with the result that the size of one bit is being made smaller and the leakage magnetic flux from the bit, i.e., the signal magnetic field, is being made lower. Such being the situation, an MR element of high sensitivity and a high signal-to-noise ratio, which is capable of providing a high magnetoresistive ratio even under a lower magnetic field, is required for reading information written on a magnetic recording medium with a high density.

Under the circumstances, a giant magnetoresistive element (GMR element), i.e., a so-called "spin-valve film", that permits to provide a high MR ratio is generally used nowadays as the MR element included in the hard disk MR head.

The spin-valve film has a stacked structure comprising a ferromagnetic layer F, a non-magnetic

layer S, a ferromagnetic layer P, and an antiferromagnetic layer, which are stacked in the order mentioned. The ferromagnetic layer P and the ferromagnetic layer F are in a magnetically non-coupled state with the nonmagnetic layer S interposed therebetween. The magnetization of the ferromagnetic layer P is pinned by the exchange bias with the antiferromagnetic material, and the magnetization of the ferromagnetic layer F can be easily rotated by, for example, an external magnetic field (e.g., an signal magnetic field). It is possible to obtain a high magnetoresistive effect by allowing the magnetization of the ferromagnetic layer F alone to be rotated by the external magnetic field so as to change the relative angle made between the magnetization directions of the two ferromagnetic layers.

The ferromagnetic layer F may be referred to as a free layer, a field-sensing layer or a magnetization free layer. The ferromagnetic layer P may be referred to as a pinned layer or a magnetization pinned layer. The nonmagnetic layer S may be referred to as a spacer layer, an interface regulating intermediate layer or an intermediate layer.

In the GMR head widely used nowadays, employed in general is a system in which a sense current is flowed in a direction parallel to the film surface to measure the resistance in the direction parallel to

the film surface. This system is generally called
a current-in-plane (CIP) system. In the case of the
CIP system, it is possible to obtain an MR ratio of
about 10 to 20%. However, it is expected that an even
higher MR ratio be required in order to achieve
reproduction at a high recording density exceeding
200 Gbit/inch^2. On the other hand, it is difficult to
obtain an MR ratio exceeding 20% when it comes to the
CIP spin-valve film available nowadays. As a result,
the situation as to how much the MR ratio can be
increased is a serious problem that must be solved for
further improving the recording density.

Under the circumstances, a current-perpendicular-
to-plane (CPP) GMR film, which is generally said to
exhibit an MR ratio higher than that of the CIP-GMR
film, is attracting attention. In the CPP system,
a sense current is flowed in a direction perpendicular
to the film surface. However, in the CPP-GMR film,
the resistance of the portion corresponding to the
thickness of the GMR film is to be measured and,
thus, the unit-area resistance is made very low.
As a result, the output as the resistance of the
element is very low so as to give rise to a problem
that it is impossible to obtain a high signal-to-noise
ratio.

In order to overcome the aforementioned problems
of the low resistance and the low MR ratio, a CPP-GMR

element provided with a resistance adjustment layer having a current confining effect is proposed in, for example, US Patent No. 6,348,274. In this prior art, however, the interlayer coupling (H_{in}) between the free

5   layer and the pinned layer is made prominent so as to give rise to a problem that the breakdown voltage is lowered.

BRIEF SUMMARY OF THE INVENTION

An object of the present invention is to provide

10   a magnetoresistive element of a high sensitivity adaptable to the high magnetic recording density required in the future, which has a low interlayer coupling field and a high breakdown voltage while maintaining appropriate resistance and a high MR ratio,

15   a magnetic head using the particular magnetoresistive element and a magnetic reproducing apparatus using the particular magnetic head.

A magnetoresistive element according to an aspect of the present invention of the present invention

20   comprises: a magnetoresistive film comprising a magnetization pinned layer, a magnetization free layer, and a nonmagnetic intermediate layer, a magnetization direction of the magnetization pinned layer substantially fixed in an external magnetic

25   field, a magnetization direction of the magnetization free layer configured to change in the external magnetic field, the nonmagnetic intermediate layer

formed between the magnetization pinned layer and the magnetization free layer and having a stacked structure of a first non-metallic intermediate layer/a metal intermediate layer/a second non-metallic intermediate

5   layer; and a pair of electrodes coupled to the magnetoresistive film and configured to provide a current in a direction substantially perpendicular to a surface of the magnetoresistive film.

A magnetic head according to another aspect of the

10   present invention of the present invention comprises the above magnetoresistive element.

A magnetic reproducing apparatus according to still another aspect of the present invention of the present invention comprises the above magnetic head,

15   and a magnetic recording medium.

BRIEF DESCRIPTION OF THE SEVERAL VIEWS OF THE DRAWING

FIG. 1 is a cross-sectional view of a magnetoresistive element according to one embodiment of the present invention;

20   FIG. 2 is a cross-sectional view of a magneto-resistive element according to another embodiment of the present invention;

FIG. 3 is a cross-sectional view of a magneto-resistive element according to another embodiment of

25   the present invention;

FIG. 4 is a cross-sectional view of a magneto-resistive element according to another embodiment of

the present invention;

FIG. 5 is a cross-sectional view of a magneto-resistive element according to another embodiment of the present invention;

FIG. 6 shows an R-H curve for Comparative Example 1a;

FIG. 7 shows an R-H curve for Example 1 of the present invention;

FIG. 8 shows the I-V characteristics for Example 1 of the present invention and Comparative Example 1a;

FIG. 9 is a perspective view showing a structure of a magnetic recording-reproducing apparatus according to one embodiment of the present invention; and

FIG. 10 is a perspective view showing a structure of a magnetic head assembly according to one embodiment of the present invention.

DETAILED DESCRIPTION OF THE INVENTION

Embodiments of the present invention will now be described with reference to the accompanying drawings.

FIG. 1 is a cross-sectional view of a magnetoresistive element (CPP-SV film) according to one embodiment of the present invention. As shown in the drawing, the CPP-SV film comprises a lower electrode 10, an underlayer 11, an antiferromagnetic layer 12, a magnetization pinned layer (pinned layer) 13, a second interface metal layer 14, a second non-metallic intermediate layer 15, a metal

intermediate layer 16, a first non-metallic

intermediate layer 17, a first interface metal layer

18, a magnetization free layer (free layer) 19,

a protective layer 20, and an upper electrode 21, which

5   are stacked on a substrate (not shown) in the order

mentioned. The pinned layer 13 is formed in contact

with the antiferromagnetic layer 12. The magnetization

of the pinned layer 13 is pinned by the exchange

coupling between the pinned layer 13 and the

10   antiferromagnetic layer 12. The magnetizing direction

of the free layer 19 is changed freely by an external

magnetic field generated from the magnetic recording

medium facing to the air-bearing surface thereof.

The pair of electrodes may be detached from top surface

15   of the uppermost layer, for example, the protective

layer 20, and bottom surface of the lowermost layer,

for example, the underlayer 11, while other conductive

layers are formed therebetween.

FIG. 2 is a cross-sectional view of a CPP-SV film

20   according to another embodiment of the present

invention. As shown in the drawing, the CPP-SV film

comprises a lower electrode 10, an underlayer 11,

an antiferromagnetic layer 12, a magnetization pinned

layer (pinned layer) 13, a second non-metallic

25   intermediate layer 15, a metal intermediate layer 16,

a first non-metallic intermediate layer 17,

a magnetization free layer (free layer) 19,

a protective layer 20, and an upper electrode 21, which
are stacked on a substrate (not shown) in the order
mentioned. In other words, the CPP-SV film shown in
FIG. 2 has a structure that the second and first

5   interface metal layers 14 and 18 are omitted from
the CPP-SV film shown in FIG. 1.

Incidentally, it is possible to increase the
number of non-metallic intermediate layers so as to
form such a structure as non-metallic intermediate

10   layer/metal intermediate layer/non-metallic
intermediate layer/metal intermediate layer/non-
metallic intermediate layer.

In the magnetoresistive element according to
the embodiments of the present invention, a stack of

15   a non-metallic intermediate layer, a metal intermediate
layer and a non-metallic intermediate layer is formed
as the intermediate layer positioned between the free
layer and the pinned layer, as shown in FIGS. 1 and 2.
Since the tow non-metallic intermediate layers are

20   separated from each other by the metal intermediate
layer, it is possible to lower interlayer magnetic
coupling acting between the free layer and the pinned
layer due to increase in the thickness of the
intermediate layer between the free layer and the

25   pinned layer. In addition, the voltage applied to each
non-metallic intermediate layer is lowered so as to
improve the breakdown voltage. These effects will now

be described.

In general, a shift H_{sh} for a bias point is generated relative to the central axis of a R-H curve of a CPP-SV film obtained by hysteresis measurement. Here, it is desirable to adjust the film so as to achieve $H_{sh} = 0$. The shift H_{sh} is represented by:

$$H_{sh} = H_{in} + H_{or} - H_d,$$

where H_{in} is RKKY-like interface coupling, H_{or} is interface coupling attributed to interface roughness, and H_d is a biasing effect produced by a leakage magnetic field from the pinned layer. Incidentally, it is possible to make H_d close to 0, i.e., Hd $\fallingdotseq$ 0, by modifying the structure of the pinned layer.

Where the stack of non-metallic intermediate layer/metal intermediate layer/non-metallic intermediate layer is inserted between the free layer and the pinned layer as in the magnetoresistive element according to the embodiments of the present invention, it is possible to increase substantially the distance between the free layer and the pinned layer, compared with the magnetoresistive element in which a single non-metallic intermediate layer is inserted between the free layer and the pinned layer. As a result, in the embodiments of the present invention, it is possible to make very small the RKKY-like interface coupling (H_{in}) and the interface coupling (H_{or}) due to the interface roughness so as to reduce the shift H_{sh}.

The breakdown voltage in the magnetoresistive element according to the embodiments of the present invention will now be described. Since the magnetoresistive element of the present invention includes a stack of non-metallic intermediate layer/metal intermediate layer/non-metallic intermediate layer, the voltage applied to a single non-metallic intermediate layer is lowered. Suppose an operating voltage V_t is applied to a magnetoresistive element. In this case, the voltage applied to a single non-metallic intermediate layer is about V_t/n in the case where n numbers of non-metallic intermediate layers (n > 1) are arranged in a magnetoresistive element, and is about $V_t/2$ in the case where two non-metallic intermediate layers are arranged in a magnetoresistive element. It follows that, where the breakdown voltage is V_B in the case where a single non-metallic intermediate layer is arranged in a magnetoresistive element, the breakdown voltage is about nV_B in the case where n numbers of non-metallic intermediate layers are arranged in a magnetoresistive element, and the breakdown voltage is about $2V_B$ in the case where two non-metallic intermediate layers are arranged in a magnetoresistive element. Incidentally, in order to improve a breakdown voltage in a magnetoresistive element having a single non-metallic intermediate layer, it is necessary

to increase the thickness of the non-metallic intermediate layer. In this case, however, unit-area resistance (RA) is also increased, with the result that the magnetoresistive element cannot be used in

5   a magnetic head.

Each layer included in the magnetoresistive element according to the embodiments of the present invention will now be described in detail.

<Morphology of Non-metallic Intermediate Layer>

10   Morphology of the non-metallic intermediate layer will now be described with reference to FIGS. 3 and 4. As shown in FIGS. 3 and 4, the non-metallic intermediate layer 15 (17) is formed of two or more phases including a conductive phase 15a (17a) and

15   an insulating phase 15b (17b). The conductive phase is present in a columnar configuration and functions as a current path. The insulating phase is formed of an oxide, an oxynitride or a nitride. The non-metallic intermediate layer 15 (17) serves to reduce the cross

20   section of a current path, sectioned with a plane parallel to the surface of the non-metallic intermediate layer, so as to confine the current. The conductive phase denotes a portion that shows ohmic conduction characteristics. Therefore, the conductive

25   phase may include a small amount of oxygen. Whether or not the non-metallic intermediate layer 15 (17) shows the ohmic conduction can be judged by measuring the

temperature characteristics of resistance within
a temperature range of between 4.2K and about 300K, or
within at least a temperature range of between 77K and
room temperature. In the case of the ohmic conduction,
the resistance falls with decrease of the temperature.
On the other hand, in the case of, for example, the
tunnel conduction, it is observed that the resistance
tends to increase with decrease of the temperature.
Also, in the case of the ohmic conduction, there is
observed in I-V (sense current-to-output voltage)
characteristics that the voltage V is not completely
proportional to the current I but tends to be slightly
shifted toward the high voltage side.

It is desirable that a size of the conductive
phase be 10 nm or less. If the size of the conductive
phase exceeds 10 nm, the current confining effect is
made very low so as to make it impossible to adjust the
unit-area resistance RA. Also, taking the effect of
improvement in MR ratio and distribution of the
conductive phase described below into consideration, it
is more desirable that the size of the conductive phase
be 5 nm or less.

It is desirable that an area ratio of the
conductive phase in the film surface of the
non-metallic intermediate layer falls in a range of 1%
to 20%. If the area ratio is lower than 1%, the
resistance of the element is made excessively high.

If the area ratio exceeds 20%, the current confining effect is decreased so as to lower the MR ratio.

It is desirable that the number density of the conductive phases in the film surface of the non-metallic intermediate layer is at least 20 per 0.1 μm^2. If the number of conductive phases per 0.1 μm^2 is smaller than 20, reduction in output of the CPP-GMR head caused by lowered sensitivity in the vicinity of the surface of the head floated on a disc and dual-peak in a track profile are observed.

On the other hand, according to observation of a planar transmission electron microscopy (TEM) image and nano-scale energy dispersive X-ray (nano-EDX) analysis, which provides a direct method for determining local composition, the element for the current path such as Cu, Ag, Au, Ru, Ir, Pt and Os is detected in the conductive phase in a larger amount than the element forming oxide (or oxynitride) constituting the matrix phase. In other words, two-dimensional fluctuation in composition is observed in the film surface. Also, where the local current characteristics are measured by, for example, conductance atomic force microscopy (AFM) or tunneling AFM (TUNA), two-dimensional resistance distribution or two-dimensional current distribution is observed within the film surface, which makes it possible to discriminate the conductive phase and the insulating phase. In the case of the

conductance AFM measurement, the portion having high
conductance (or low resistance) corresponds to the
conductive phase. In the case of the TUNA measurement,
which is carried out under a constant voltage, the

5   portion where high current is observed corresponds to
the conductive phase.

FIGS. 3 and 4 show two types of structures of the
non-metallic intermediate layers. FIG. 3 covers the
case where conductive phases of the non-metallic

10   intermediate layers 15, 17 are arranged off
registration along the direction perpendicular to the
film surface. FIG. 4 covers the case where the
conductive phases of the non-metallic intermediate
layers 15, 17 are arranged in registration along the

15   direction perpendicular to the film surface. Each of
these structures produces the effect of increasing the
resistance of the element to fall within an optimum
range.

<Materials for non-metallic intermediate layer>

20   The non-metallic intermediate layer is constituted
by a conductive phase and an insulating phase. The
conductive phase of the non-metallic intermediate layer
contains at least one element selected from the group
consisting of Cu, Au, Ag, Pt, Pd, Ir and Os. The

25   portion in which the conductive element is contained in
a large amount forms the conductive phase performing
the ohmic conduction. In this case, it is desirable

that the amount of conductive element be at least

1 atomic % and smaller than 50 atomic % based on the

entire non-metallic intermediate layer. Under the

particular condition, it is possible to form the

5   two-dimensional distribution of the conductive

characteristics described above.

The insulating phase of the non-metallic

intermediate layer is formed of an oxide, an oxynitride

or a nitride of at least one element selected from the

10   group consisting of boron (B), silicon (Si), germanium

(Ge), tantalum (Ta), tungsten (W), niobium (Nb),

aluminum (Al), molybdenum (Mo), phosphorus (P),

vanadium (V), arsenic (As), antimony (Sb), zirconium

(Zr), titanium (Ti), zinc (Zn), lead (Pb), thorium

15   (Th), beryllium (Be), cadmium (Cd), scandium (Sc),

lanthanum (La), yttrium (Y), praceodymium (Pr),

chromium (Cr), tin (Sn), gallium (Ga), indium (In),

rhodium (Rh), palladium (Pd), magnesium (Mg), lithium

(Li), barium (Ba), calcium (Ca), strontium (Sr),

20   manganese (Mn), iron (Fe), cobalt (Co), nickel (Ni),

rubidium (Rb), and a rare earth metal.

In particular, B, Si, Ge, W, Nb, Mo, P, V, Sb, Zr,

Ti, Zn, Pb, Cr, Sn, Ga, Fe, Co and a rare earth metal

of the above elements tend to form a crystalline oxide.

25   On the other hand, Al and Ta tend to form an amorphous

oxide. Deficiency or surplus of oxygen atoms in the

crystalline oxide tends to affect the conductive

characteristics compared with the case of the amorphous oxide. Therefore, the crystalline oxide is advantageous in that a two-dimensional modulation of the conductive characteristics may be formed easily in the film surface of the non-metallic intermediate layer, and in that the composition modulation may be formed easily in generation of an alloy phase with Cu, Ag, Au, Ru, Ir, Pt and Os described above as the element for the conductive phase.

In forming the non-metallic intermediate layer, oxidation, oxynitriding or nitriding is carried out in many cases by using alloys of the elements noted above. The method for performing the oxidation, oxynitriding or nitriding includes, for example, natural oxidation in which oxygen gas is simply introduced into a deposition chamber, ion-assisted oxidation (or oxynitriding) in which oxygen gas is introduced into a deposition chamber and a deposited film is irradiated with ions of Ar of N_2, and ion beam oxidation (or nitriding) in which a deposited film is irradiated with oxygen (or nitrogen) ions.

Incidentally, the two non-metallic intermediate layers may be different from each other in the thickness and the composition.

<Metal Intermediate Layer>

The metal intermediate layer is formed of a thin film of a metal such as Al, Cu, Ag, Au, Ru, Ir, Pt or

Os. From the point of view of the improvement in MR ratio, it is most desirable to use a Cu thin film. From the point of view of oxidation resistance, it is also desirable to use a thin film of Au, Pt or Ru.

5   It is desirable that the element used for forming the metal intermediate layer is equal to that contained in the non-metallic intermediate layer. FIGS. 3 and 4 cover the case where the metal intermediate layer 16 and the conductive phases 15a, 17a of the non-metallic

10   intermediate layers 15, 17 are formed of the same material. Also, the metal intermediate layer 16 and the conductive phases 15a, 17a of the non-metallic intermediate layers 15, 17 may be formed of different materials as shown in FIG. 5. In this case, it is

15   possible for a part of the metal intermediate layer to intrude into the conductive phases 15a, 17a of the non-metallic intermediate layers 15, 17, as shown in FIG. 5.

The metal intermediate layer may be formed of

20   a single layer or a plurality of layers. For example, it is conceivable to employ a stacked structure of Cu/Al/Cu or Au/Al/Au, where Al has a low electron scattering property of and brings about a large spin diffusion length. In this case, it is desirable to use

25   a metal that is unlikely to be oxidized such as Au, Ru or Pt for forming the portion of the metal intermediate layer contacting with the non-metallic intermediate

layer.

It is desirable for the metal intermediate layer
to have a thickness of 0.5 nm or more. If the
thickness of the metal intermediate layer is smaller
than 0.5 nm, the mixing with the lower or upper
non-metallic intermediate layer is caused by the energy
of the incoming particles in the deposition process.
As a result, the metal intermediate layer is put in
a state of being taken in the non-metallic intermediate
layer. It follows that the metal intermediate layer
fails to separate the two non-metallic intermediate
layers, resulting in failure to produce the effects in
terms of reduction of H_{in} and improvement of the
breakdown voltage. It is desirable for the metal
intermediate layer to have a thickness of 20 nm or
less. If the thickness of the metal intermediate layer
exceeds 20 nm, the number of electrons performing
ballistic conduction between the two non-metallic
intermediate layers tends to be decreased. In other
words, the retention of spin information is lowered by
spin diffusion so as to significantly decrease the MR
ratio. Where the thickness of the metal intermediate
layer is not larger than 20 nm, the reduction of the MR
ratio is moderate.

Incidentally, where composition analysis is
performed by EDX with cross-sectional TEM observation
in a nano-scale region of the stack of non-metallic

intermediate layer/metal intermediate layer, gradation
is observed in the oxygen distribution. In other
words, it is not strictly necessary that the
non-metallic intermediate layer be clearly

5   discriminated from the metal intermediate layer.
Likewise, gradation (composition modulation) in the
distribution of an element other than oxygen may be
observed between the metal intermediate layer and the
non-metallic intermediate layer.

10   <Effect of first interface metal layer>

In the magnetoresistive film shown in FIG. 1, the
first interface metal layer 18 is formed between the
free layer 19 and the first non-metallic intermediate
layer 17. The first interface metal layer 18

15   contributes to make magnetic properties of the free
layer 19 softer. To be more specific, since (111)
orientation and crystalline properties of the free
layer 19 are improved because of the first interface
metal layer 18 so as to relax film stress caused by

20   lattice mismatch, coercivity Hc of the free layer 19 is
lowered. On the other hand, if the free layer 19 is in
direct contact with the non-metallic intermediate layer
17 formed of an oxide, an oxynitride or a nitride, the
free layer 19 tends to be affected by oxygen or

25   nitrogen so that coercivity thereof is increased. Such
being the situation, it is desirable to form the first
interface metal layer 18 between the free layer 19 and

the first non-metallic intermediate layer 17.

<Effect of second interface metal layer>

In the magnetoresistive film shown in FIG. 1,
the second interface metal layer 14 is formed between
the pinned layer 13 and the second non-metallic
intermediate layer 15. The second interface metal
layer 14 produces an effect of preventing oxidation of
the pinned layer 13 during the oxidizing process for
forming the second non-metallic intermediate layer 15.
Also, where the second interface metal layer 14 is
formed, it is possible to prevent the pinned layer 13
from being oxidized by oxygen diffused from the second
non-metallic intermediate layer 15 in an annealing
process. Therefore, it is possible to suppress
degradation in exchange coupling field by the pinned
layer 13.

Also, gradation of composition (composition
modulation) may be observed in a direction
perpendicular to the film surface in a cross section of
a stack of interface metal layer/non-metallic
intermediate layer/metal intermediate layer/non-
metallic intermediate layer/interface metal layer.
To be more specific, it is not always necessary that
clear separation of the composition be observed in
nano-scale composition analysis with cross-sectional
TEM observation. Particularly, in the case of using
the same material for forming the interface metal

layer, the conductive phase of the non-metallic intermediate layer and the metal intermediate layer, the interfaces between the adjacent layers observed by cross-sectional TEM may possibly be made unclear.

<Explanation of free layer>

It is possible to use Co, Fe, Ni or an alloy containing these elements as a ferromagnetic material constituting the free layer. Typically, a $Co_{90}Fe_{10}$ alloy, a CoFeNi alloy, or a $Ni_{80}Fe_{20}$ alloy (permalloy) is used for the free layer.

The free layer preferably has a face-centered cubic (fcc) structure and is oriented such that the (111) plane is made parallel to the film surface in order to exhibit satisfactory soft magnetic properties. Incidentally, the orientation of the free layer may partly include hcp (0001) orientation or bcc (110) orientation.

It is desirable to control the free layer in the anisotropic property and the domain configuration by applying a magnetic bias (biasing control) to the free layer by means of a hard magnetic film (hard biasing film) or an antiferromagnetic film (patterned biasing film).

<Explanation of pinned layer>

It is possible to use, for example, a $Co_{90}Fe_{10}$ film, a $Fe_{50}Co_{50}$/Cu stacked film or a $Ni_{80}Fe_{20}$ film as the ferromagnetic material constituting the pinned

layer, like the material constituting the free layer.

It is possible for the pinned layer to have a so-called "synthetic structure". The basic structure of the synthetic pinned layer is a stacked structure of

5   ferromagnetic layer/nonmagnetic layer/ferromagnetic layer. In this structure, the two ferromagnetic layers are antiferromagnetically coupled with each other through the nonmagnetic layer interposed therebetween. Ruthenium (Ru) is used typically as a material of the

10   nonmagnetic layer.

The magnetization of the pinned layer is pinned in one direction by exchange coupling with the antiferromagnetic layer as described above. The material of the antiferromagnetic layer includes

15   a Mn-based alloy containing Pt, Ir, Rh, Ru or Pd. The typical antiferromagnetic materials include a PtMn alloy, a PtPdMn alloy and an IrMn alloy.

Examples

Examples of the present invention will now be

20   described.

Example 1:

A lower electrode film 10 was formed in a thickness of about 100 nm on a Si (100) substrate, followed by patterning the lower electrode film 10 by

25   photolithography and dry etching. Then, a CPP-SV film of the structure shown in FIG. 1, which included the layers 11 to 20 given below, was deposited on the lower

electrode 10 (Example 1). Each layer was deposited
with a DC magnetron sputtering apparatus.

Underlayer 11: Ta/Ru;

Antiferromagnetic layer 12: PtMn;

5   Pinned layer 13: CoFe/Ru/CoFe;

Second interface metal layer 14: Cu;

Second non-metallic intermediate layer 15:
an oxidized product of AlCu (thickness: 0.7 nm);

Metal intermediate layer 16: Cu (2 nm);

10   First non-metallic intermediate layer 17:
an oxidized product of AlCu (thickness: 0.7 nm);

First interface metal layer 18: Cu;

Free layer 19: CoFe;

Protective layer 20: Cu/Ta.

15   It should be noted that, in Example 1, the
intermediate layer between the pinned layer and the
free layer is made of a stack of the second interface
metal layer (Cu), the second non-metallic intermediate
layer (oxidized AlCu), the metal intermediate layer

20   (Cu), the first non-metallic intermediate layer
(oxidized AlCu) and the first interface metal
layer (Cu).

For comparison, CPP-SV films similar to that for
Example 1, except that the intermediate layer between

25   the pinned layer and the free layer was made of a stack
of the second interface metal layer (Cu), non-metallic
intermediate layer (oxidized AlCu layer) and first

interface metal layer (Cu) are formed as Comparative
Example 1a and Comparative Example 1b. Incidentally,
the non-metallic intermediate layer for the Comparative
Example 1a was prepared by oxidizing an AlCu film

5   having a thickness of 0.7 nm and the non-metallic
intermediate layer for the Comparative Example 1b was
prepared by oxidizing an AlCu film having a thickness
of 1.0 nm.

The oxidation for forming the non-metallic

10   intermediate layer was carried out by ion-assisted
oxidation (IAO) in which oxygen gas is introduced into
a chamber and a deposited film is irradiated with Ar
ions. The amount of oxygen introduced into the chamber
was controlled to fall in a range of 1 kL to 20 kL.

15   The CPP-SV film thus formed was patterned using
photolithography and ion milling. The size of the
CPP-SV film fell in a range of 0.2 μm to 5.0 μm, and
the CPP-SV film was patterned is a square. Then,
an upper electrode 21 was formed.

20   The magnetic characteristics, the MR ratio and the
I-V characteristics of the CPP-SV film were measured
for each of Example 1, Comparative Example 1a and
Comparative Example 1b. The MR ratio was obtained from
the dR-R plot. To be more specific, when R was plotted

25   on the X-axis and dR was plotted on the Y-axis, the MR
ratio was defined as inclination of a dR-R straight
line multiplied by 100. The unit-area resistance RA

was calculated from R-1/A plot (where A denotes the element area). In this case, when 1/A was plotted on the X-axis and R was plotted on the Y-axis, the unit-area resistance RA was defined as inclination of a R-1/A straight line.

The MR ratio was found to be 2.7% for Example 1 and 2.5% for Comparative Example 1a. Thus, Example 1 and Comparative Example 1a were found to be substantially equal to each other in the MR ratio.

The unit-area resistance RA was found to be 350 m$\Omega \mu$m^2 for Example 1 and 300 m$\Omega \mu$m^2 for Comparative Example 1a. It has been found that, in Example 1, increase in the unit-area resistance RA can be suppressed up to some extent so as to fall in a range (i.e., 500 m$\Omega \mu$m^2 or less) where the magnetoresistive element can be used for the magnetic head under ultra-high recording density of 100 Gbpsi or more.

FIG. 6 shows the R-H curve for Comparative Example 1a, and FIG. 7 shows the R-H curve for Example 1. As apparent from these drawings, the shift H_{sh} for Comparative Example 1a was about 30 Oe. On the other hand, the shift H_{sh} for Example 1 was lowered to about 5 Oe, supporting that the magnetoresistive element of the present invention exhibits highly excellent characteristics. Example 1 was found to exhibit a substantially just bias point.

FIG. 8 shows the I-V characteristics for Comparative Example 1a and Example 1. In Comparative Example 1a, the breakdown voltage V_B was found to be about 350 mV. On the other hand, the breakdown voltage

5　　V_B for Example 1 was improved to about 750 mV.

In Comparative Example 1b, the unit-area resistance RA was high, i.e., about 2.0 Ωcm^2. In addition, the MR ratio was lowered to 1.5%. Also, in Comparative Example 1b, the breakdown voltage V_B was

10　　400 mV and, thus, an appreciable improvement was not observed.

Examples 2 to 4 and Comparative Examples 2 to 4:

Experiments were conducted by forming CPP-SV films of the structure similar to that for Example 1 or

15　　Comparative Example 1a using a material other than the oxide of the AlCu alloy for forming the non-metallic intermediate layer.

To be more specific, in Examples 2 to 4, the intermediate layer between the pinned layer and the

20　　free layer was made of a stack of the second interface metal layer, the second non-metallic intermediate layer, the metal intermediate layer, the first non-metallic intermediate layer and the first interface metal layer (referred to as a dual-layer as to the non-

25　　metallic intermediate layers).

On the other hand, in the Comparative Examples 2 to 4, the intermediate layer between the pinned layer

and the free layer was of a stack of the second interface metal layer, the non-metallic intermediate layer and the first interface metal layer (referred to as a single-layer as to the non-metallic intermediate

5   layer).

The material of the non-metallic intermediate layer was as follows:

Example 2, Comparative Example 2: an oxidized product of $Cr_{90}Cu_{10}$ (thickness: 0.65 nm);

10   Example 3, Comparative Example 3: an oxidized product of $(Cr_{0.9}Cu_{0.1})_{97}B_3$ (thickness: 0.9 nm);

Example 4, Comparative Example 4: an oxidized product of $(Cr_{0.9}Cu_{0.1})_{95}Hf_3B_2$ (thickness: 0.9 nm).

The materials of the other layers of the CPP-SV

15   film were equal to those for Example 1.

Table 1 shows the unit-area resistance RA, the MR ratio, and the breakdown voltage (V_B) for each of the CPP-SV films. As shown in Table 1, each of Examples 2 to 4 can provide the breakdown voltage (V_B) 500 mV or

20   more.

Table 1

	Structure for non-metallic intermediate layer	Material of non-metallic intermediate layer	RA (mΩ μm^2)	MR ratio (%)	V$_B$ (mV)
Comparative Example 2	Single-layer	Cr$_{90}$Cu$_{10}$-O [0.65 nm]	300	5.1	280
Example 2	Dual-layer		550	3.0	520
Comparative Example 3	Single-layer	(Cr$_{0.9}$Cu$_{0.1}$)$_{97}$B$_3$-O [0.9 nm]	250	4.9	320
Example 3	Dual-layer		490	2.8	630
Comparative Example 4	Single-layer	(Cr$_{0.9}$Cu$_{0.1}$)$_{95}$Hf$_3$B$_2$-O [0.7 nm]	320	5.5	300
Example 4	Dual-layer		600	3.3	590

The magnetic head having the magnetoresistive
element according to the embodiment of the present
invention and the magnetic recording-reproducing
apparatus having the particular magnetic head installed
therein will now be described. The magnetoresistive
element according to the embodiment of the present
invention can be installed in a magnetic recording-
reproducing apparatus by incorporating the
magnetoresistive element in, for example, a read-write
integral type magnetic head assembly.

FIG. 9 is a perspective view schematically showing
the structure of a magnetic recording-reproducing
apparatus 150. The magnetic recording-reproducing
apparatus 150 is of a type using a rotary actuator.
As shown in the drawing, a perpendicular magnetic
recording disk 151 is mounted to a spindle 152 and is
rotated in the direction denoted by an arrow A by
a motor (not shown) in response to control signals
supplied from a drive controller (not shown).
The magnetic recording-reproducing apparatus 150 may be
provided with a plurality of disks 151.

A head slider 153 for writing data in and for
reading data from the disk 151 is mounted on the tip of
a suspension 154. A magnetic head including the
magnetoresistive element according to the embodiment of
the present invention is formed on the tip portion of
the head slider 153. When the disk 151 is rotated,

the air-bearing surface (ABS) of the head slider 153 is
held floating by a prescribed flying height from the
surface of the disk 151. Incidentally, the magnetic
recording-reproducing apparatus may be of a contact

5   type that the head slider 153 is in contact with the
disk 151.

The suspension 154 is connected to one end of an
actuator arm 155 including a bobbin portion for holding
a driving coil (not shown) on the other end. A voice

10   coil motor 156, which is one of a linear motor, is
arranged on the other end of the actuator arm 155.
The voice coil motor 156 comprises a driving coil (not
shown) wound onto the bobbin portion of the actuator
arm 155 and a permanent magnet and a counter yoke

15   arranged to face each other with the driving coil
sandwiched therebetween where these members constitute
a magnetic circuit. The actuator arm 155 is held by
ball bearings (not shown) arranged at upper and lower
portions of a pivot 157 and can be rotated by the voice

20   coil motor 156.

FIG. 10 is a perspective view showing the magnetic
head assembly 160 in a magnified fashion, which is
viewed from the disk side. To be more specific, the
magnetic head assembly 160 comprises the actuator arm

25   155 including a bobbin portion for holding the driving
coil, and the suspension 154 is connected to one end of
the actuator arm 155. The head slider 153 having

the magnetic head including the magnetoresistive
element according to the embodiment of the present
invention is mounted on the tip of the suspension 154.
The suspension 154 includes lead wires 164 for writing

5   and reading signals. The lead wires 164 are
electrically connected to each of the electrodes of
the magnetic head formed on the head slider 153.
A reference numeral 165 shown in the drawing denotes
electrode pads of the magnetic head assembly.

10   According to the present invention, it is possible to
read without fail the data recorded in the magnetic
recording disk 151 even at a recording density markedly
higher than that in the prior art by using the magnetic
head including the magnetoresistive element described

15   above.

Additional advantages and modifications will
readily occur to those skilled in the art. Therefore,
the invention in its broader aspects is not limited to
the specific details and representative embodiments

20   shown and described herein. Accordingly, various
modifications may be made without departing from the
spirit or scope of the general inventive concept as
defined by the appended claims and their equivalents.